Idaho National Engineering and Environmental Laboratory

Command and Control Architectures for Autonomous Micro-Robotic Forces

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FY01 Project Objectives

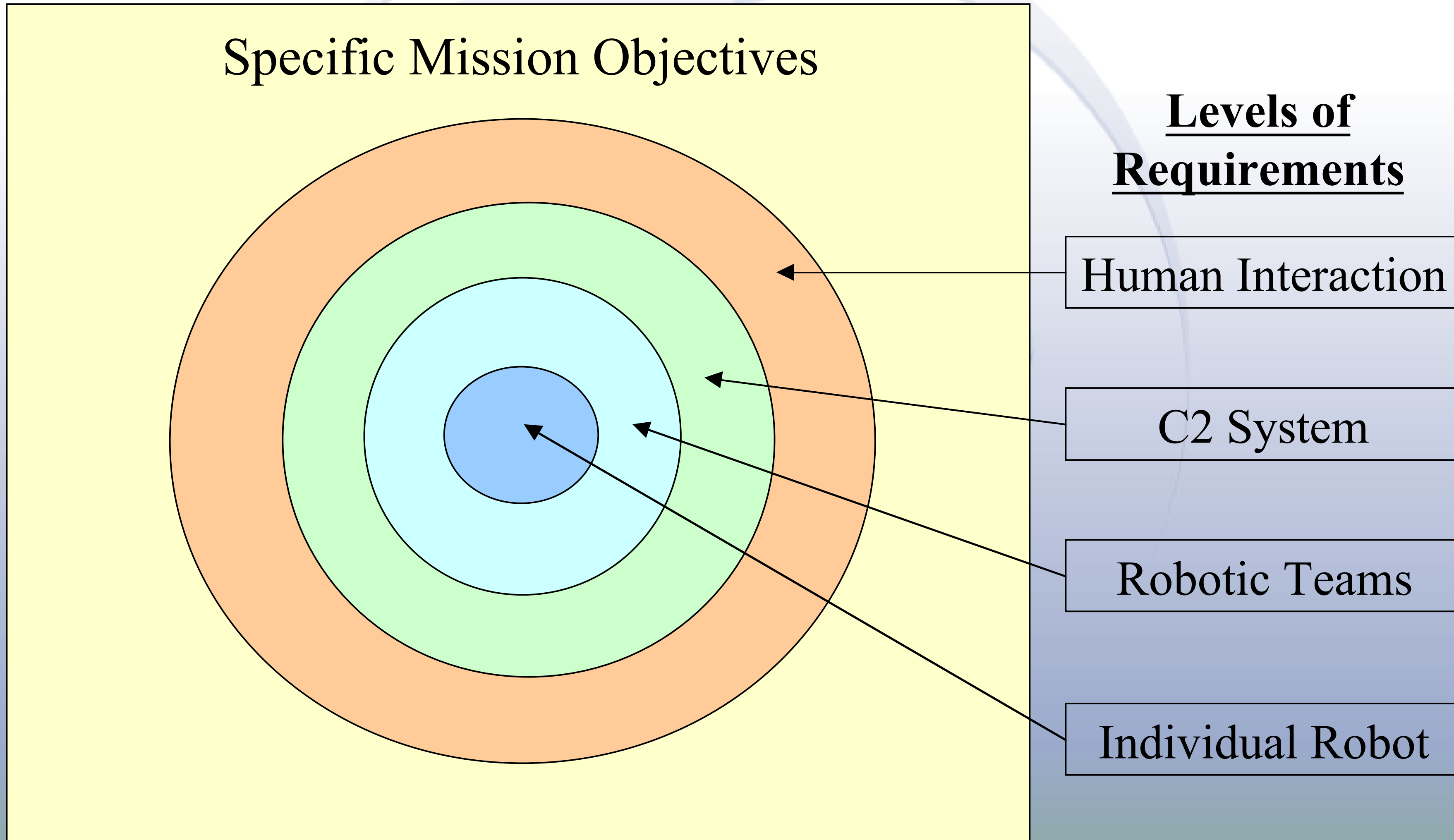
Project Goal:

Examine Command and Control structures / methodologies and associated autonomous behaviors which will permit planning, tasking, deployment, and re-tasking of a large-scale force of robotic units by a single operator.

FY01 Tasking:

- **Build upon FY00 work and develop an Operator Control Unit (OCU) to facility one operator to many robot interaction**
- **Develop a system to conduct mission profile analysis and planning for robotic force deployment**
- **Develop individual and collective behaviors to support robotic force deployment.**

Holistic View of Robotic System Development



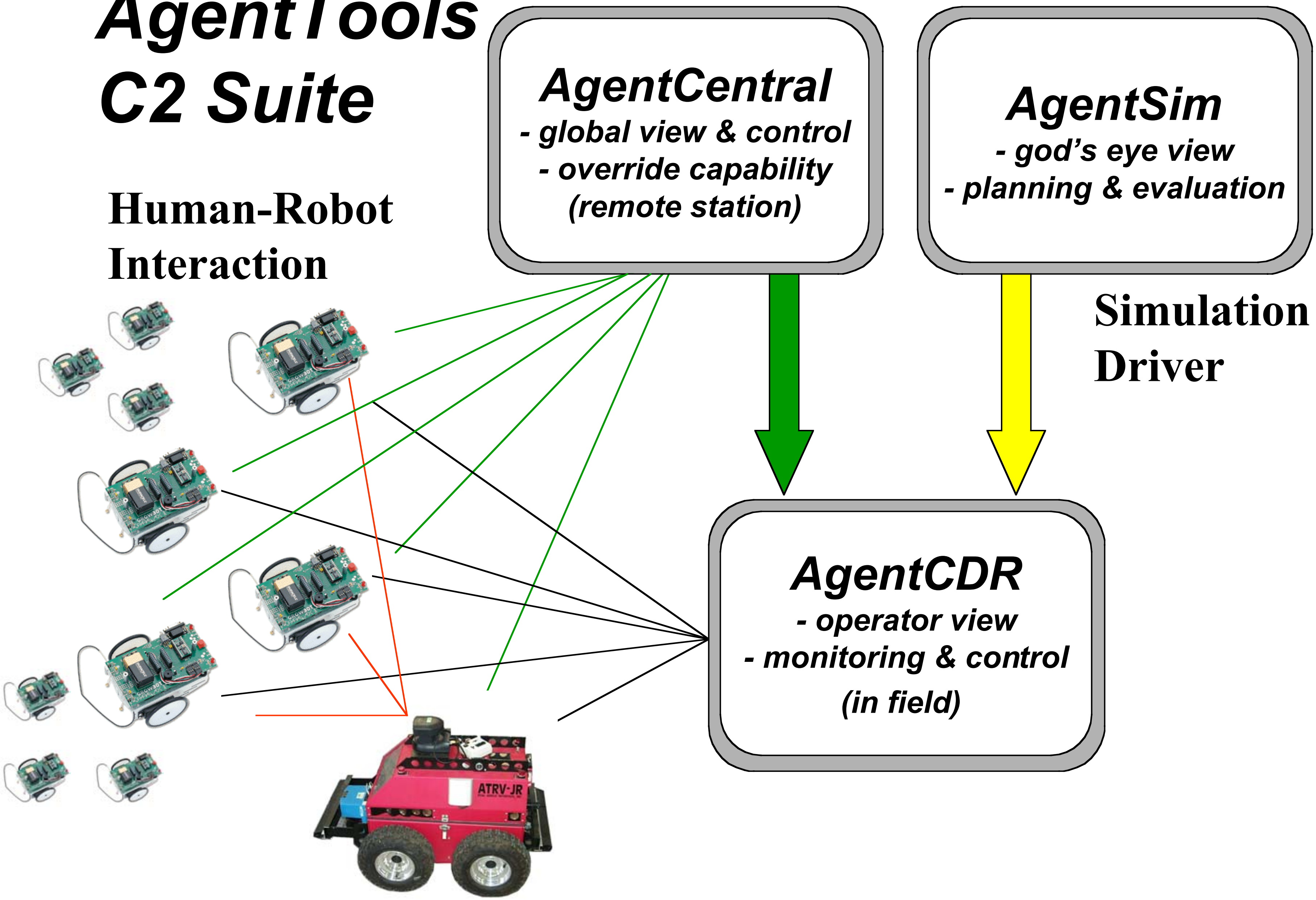
Mission tasking of robotic forces

Command and Control Insights

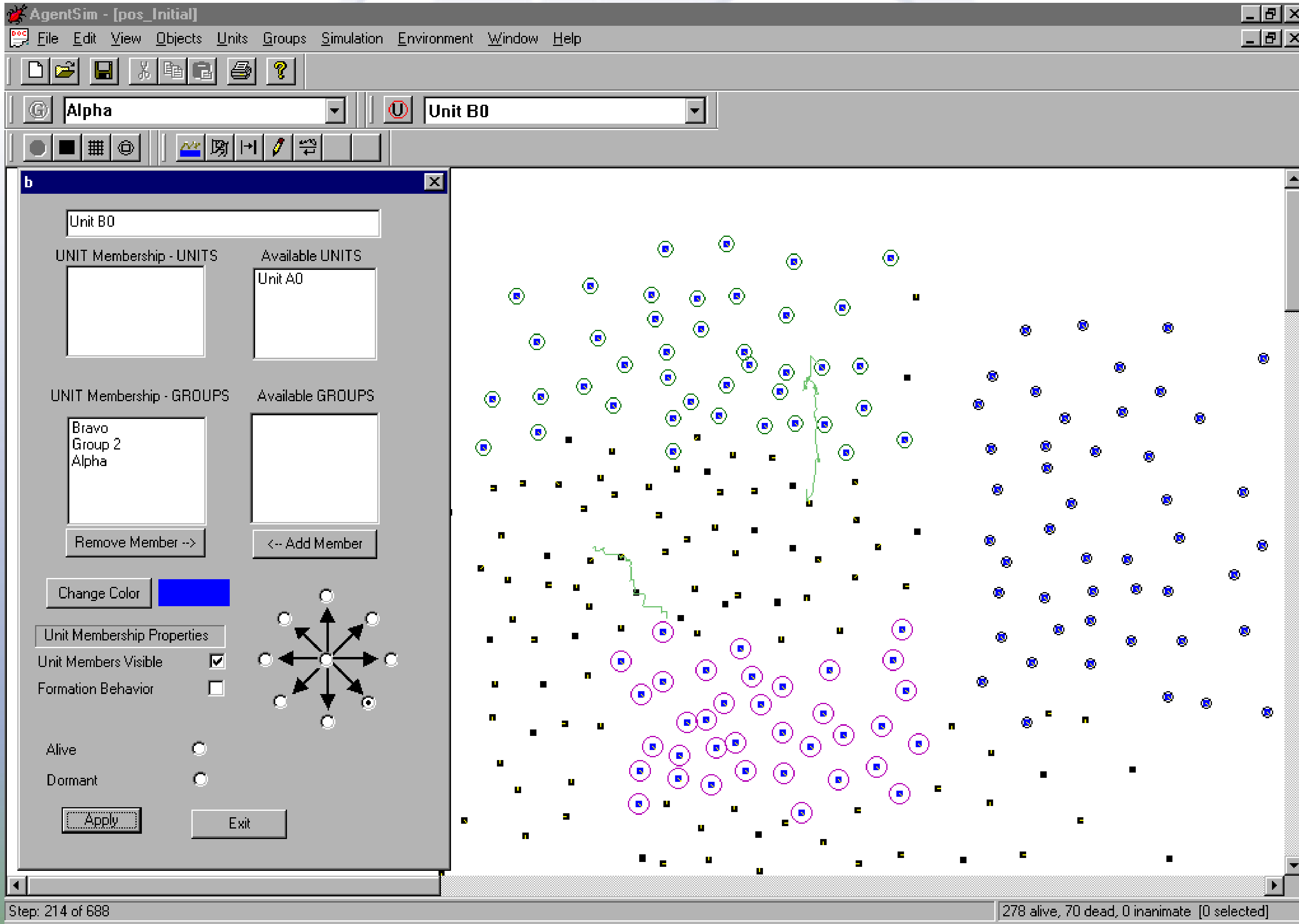
Fleet Exercise June 2001

- **Communications**
  - **Primary, Secondary, Tertiary**
  - **Bellringers**
- **Battlespace Management**
  - **Space management**
  - **Asset Coordination**
- **Preplan to replan**
- **Commander Confidence**

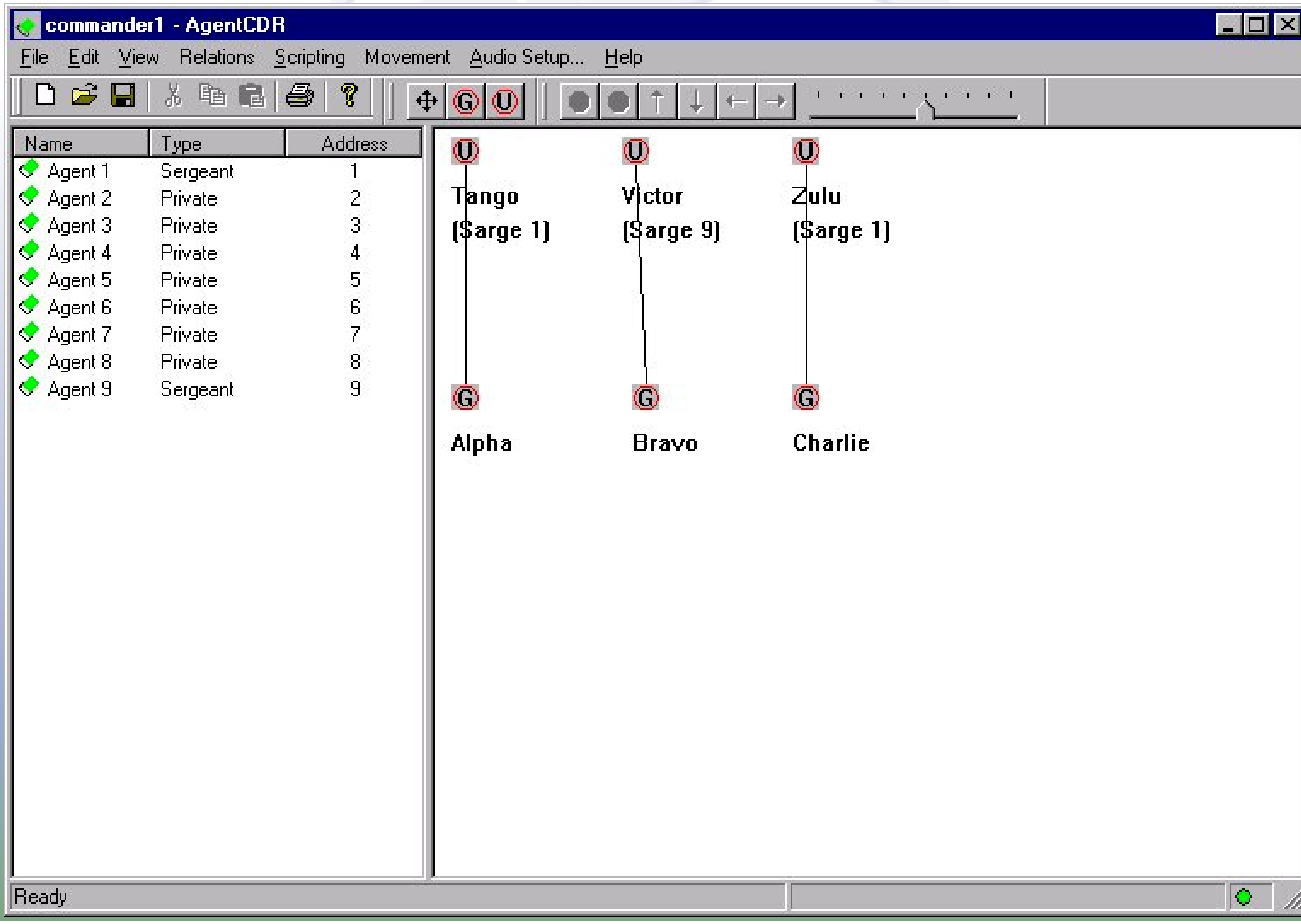
AgentTools C2 Suite



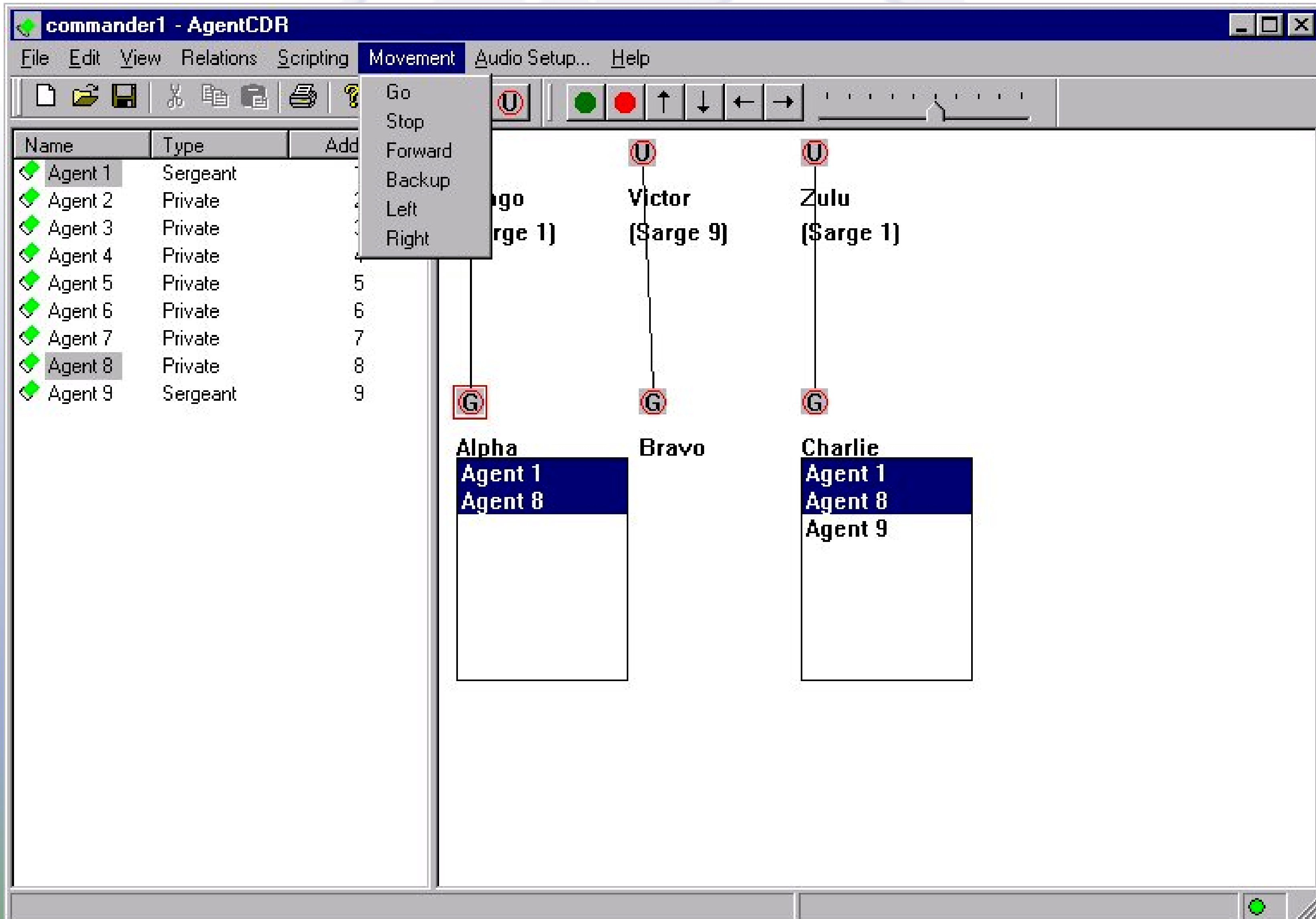
AgentSim - Simulation Tool



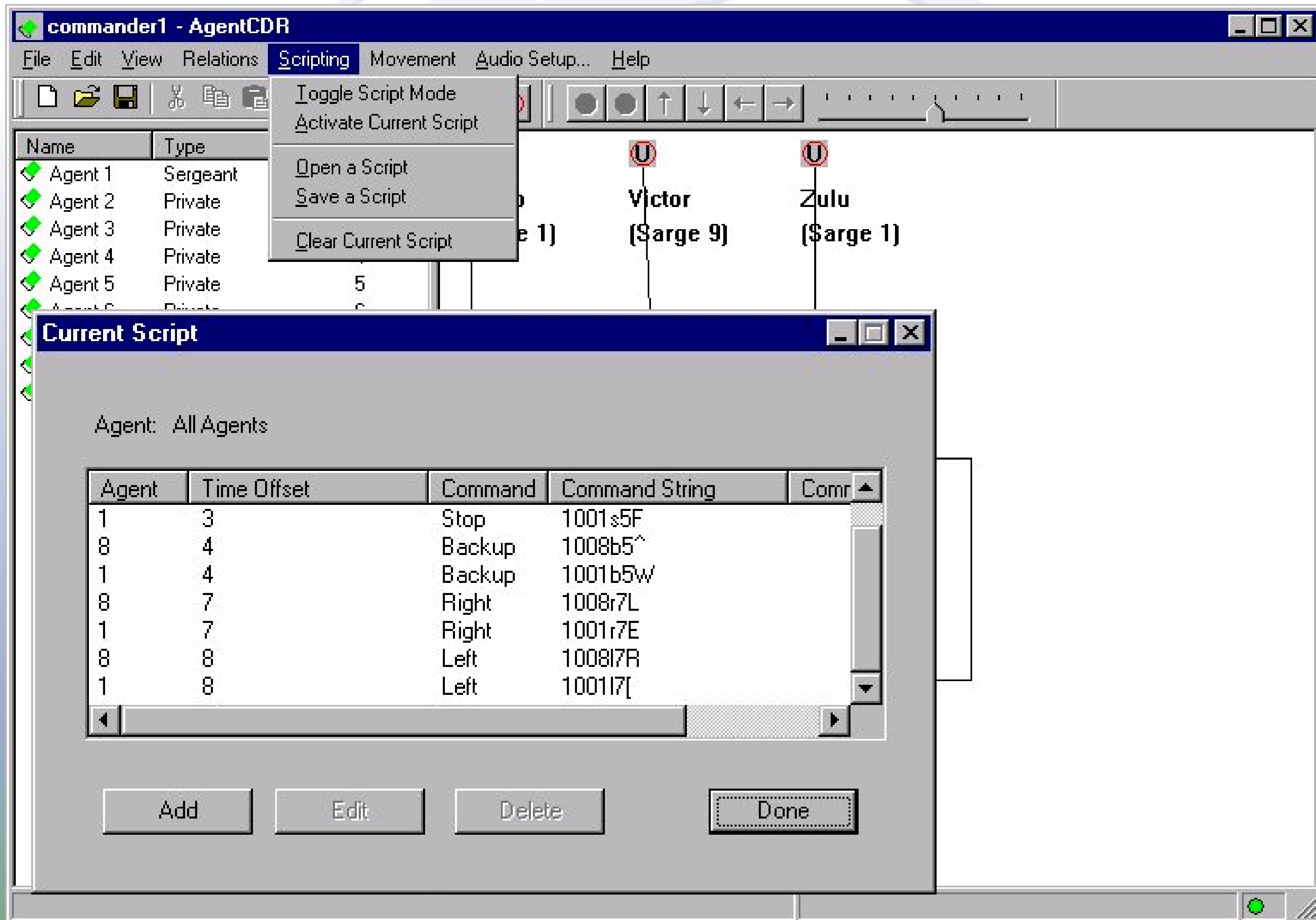
AgentCDR - OCU

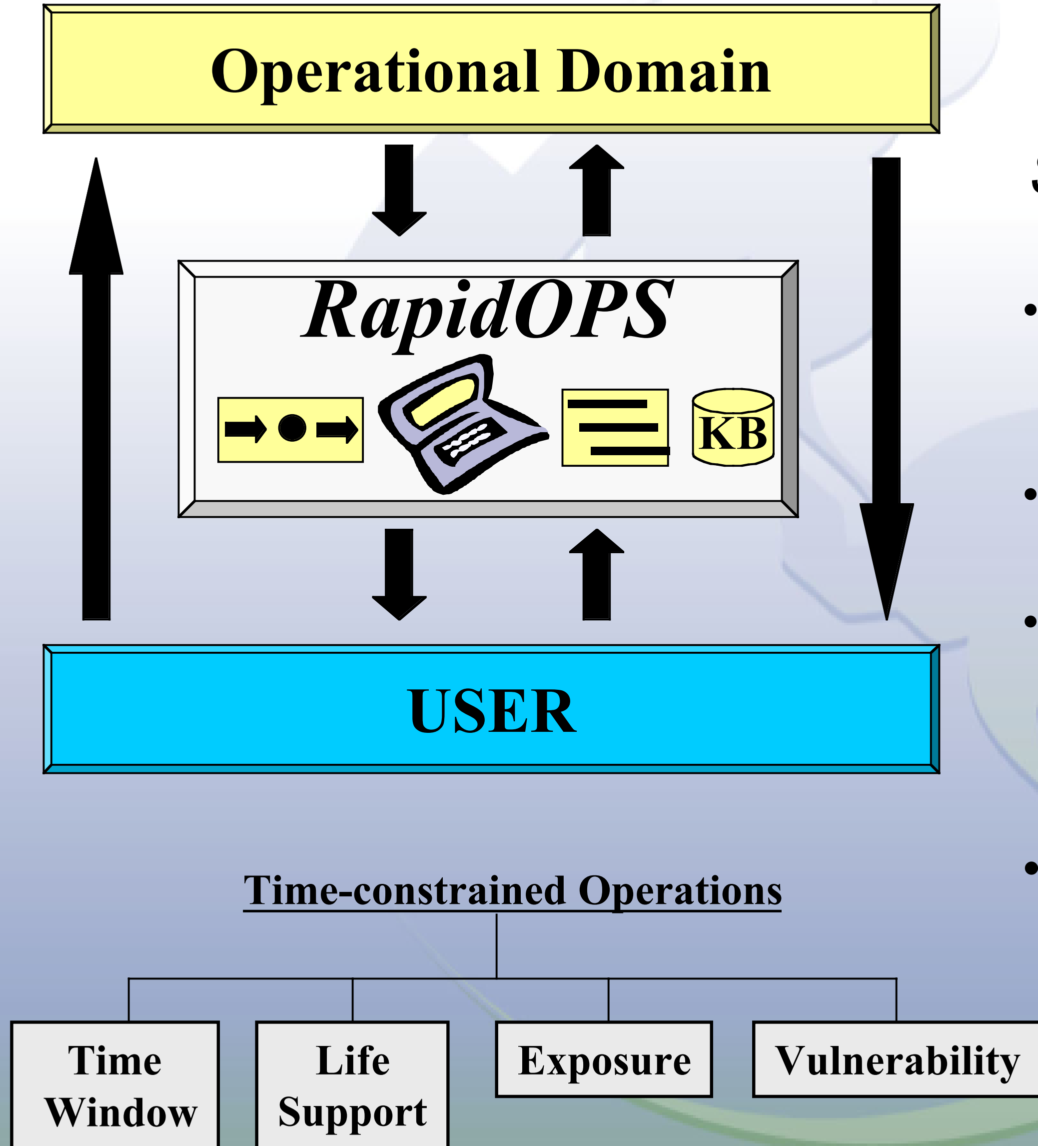


AgentCDR - Dynamic Grouping



AgentCDR - Event Scripting





An Intelligent Planning Support System for Robotic Force Deployment

- *Operational design, planning, and analysis support tool for time-constrained operations*
- *Based on a proven cycle time reduction methodology,*
- *Linked to an underlying knowledge base, and an Intelligent-aided, graphical user interface.*
- <u>*System is operationally implemented and proven!*</u>

Robotic System Characteristics

- **Emergent Behavior – As in a colony of ants, intelligent, complex behavior emerges from the interactions of multiple robots each driven by simple behaviors.**
- **High Fault Tolerance – By distributing the task across a loosely coupled population of robots, the collective can succeed even when particular robots fail.**
- **Redundancy – The behavior of each robot can be validated / duplicated by its peers.**
- **Cooperative Behavior – We can exploit synergistic behavior impossible with only one to several robots.**
- **Modulated Diversity – As in biological systems, an appropriate level of diversity adds richness to the capabilities of the collective and makes it more robust to environmental changes.**
- **Low Cost – Small scale robots can potentially be used as a disposable resource**

Desired Platform Characteristics

- **Small in size with a cross section between 2 to 4 inches.**
- **Cheap with ultimate production costs less than $100 per unit.**
- **Reactive in nature possessing only a local awareness.**
- **Autonomous - possessing a self-sufficient behavior set.**
- **Interactive - possessing the ability to exchange information with other robots and / or human operators.**
- **Able to be commanded by human operators**
- **Deployed in medium to large groups.**
- **Capable of interfacing to various mission-specific sensors**
- **Non-GPS reliant.**

Approach - Minimalist View

What is the minimal capability needed to achieve the end goal?

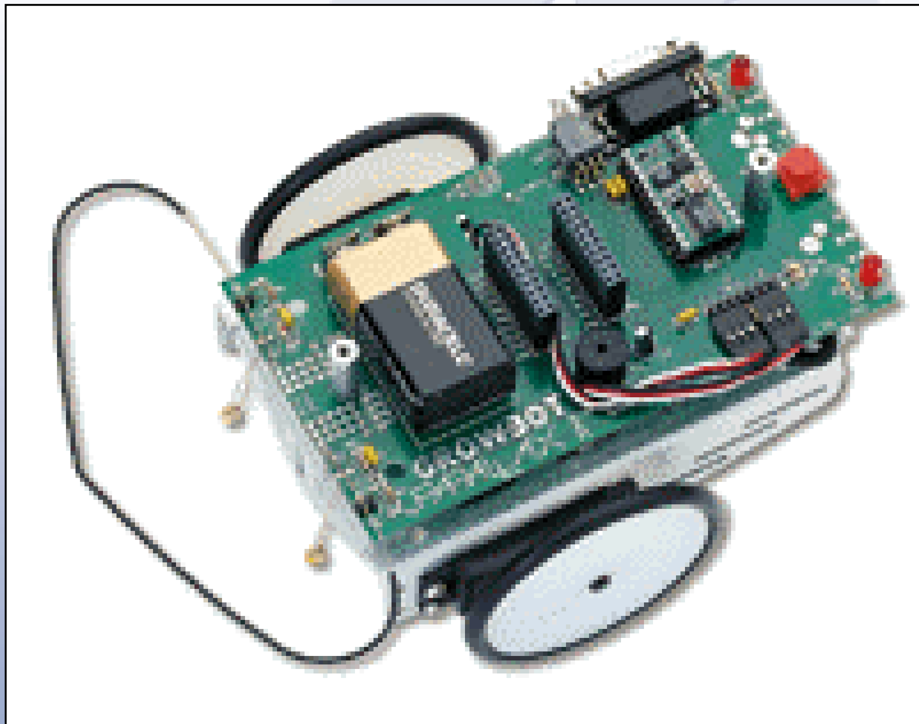
Direct Relevance to Distributed Robotic Systems

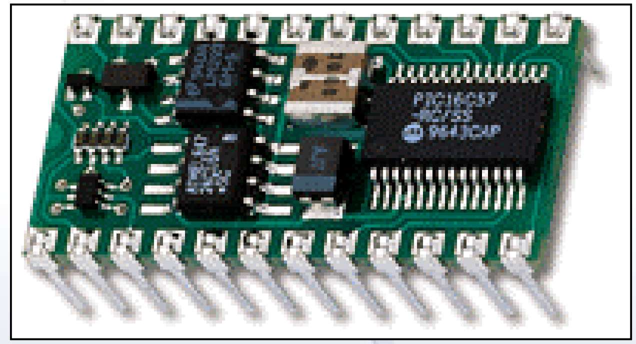
- **Cost**
- **Complexity (Keep it simple)**
- **Reliability**
  - **less to break**
  - **less is lost if it does break**
  - **other can fill in when it does break**

Potential Limitations on Individual and Collective capabilities but,
➡ the goal we are trying to achieve is not a robotics system that does everything, but one which assists the human element in tasks which are not otherwise achievable or are not achievable without exceptional costs/risks.

Robot Platform

Growbot™ by Parallax



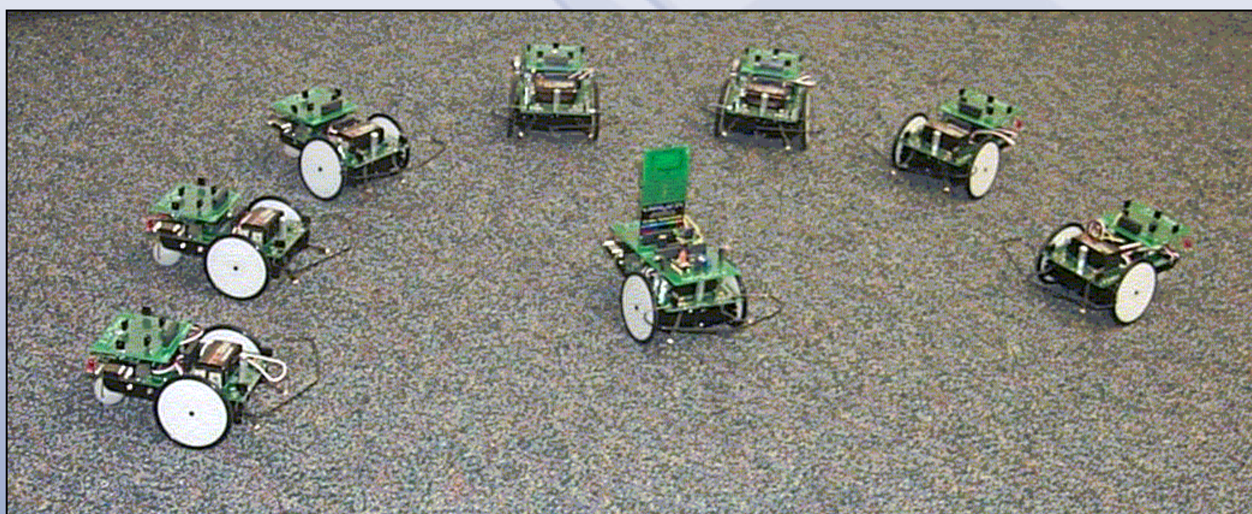


Basic Stamp 2 Characteristics

Cost:	$50 one per robot
Processor:	microchip pic16c57
Package:	24-pin dip
Clock speed:	20Mhz
Ram:	32 bytes ram
Program size:	2K EEPROM
Voltage:	5-15 VDC
Current draw:	8mA (running)
	100microA (sleep)

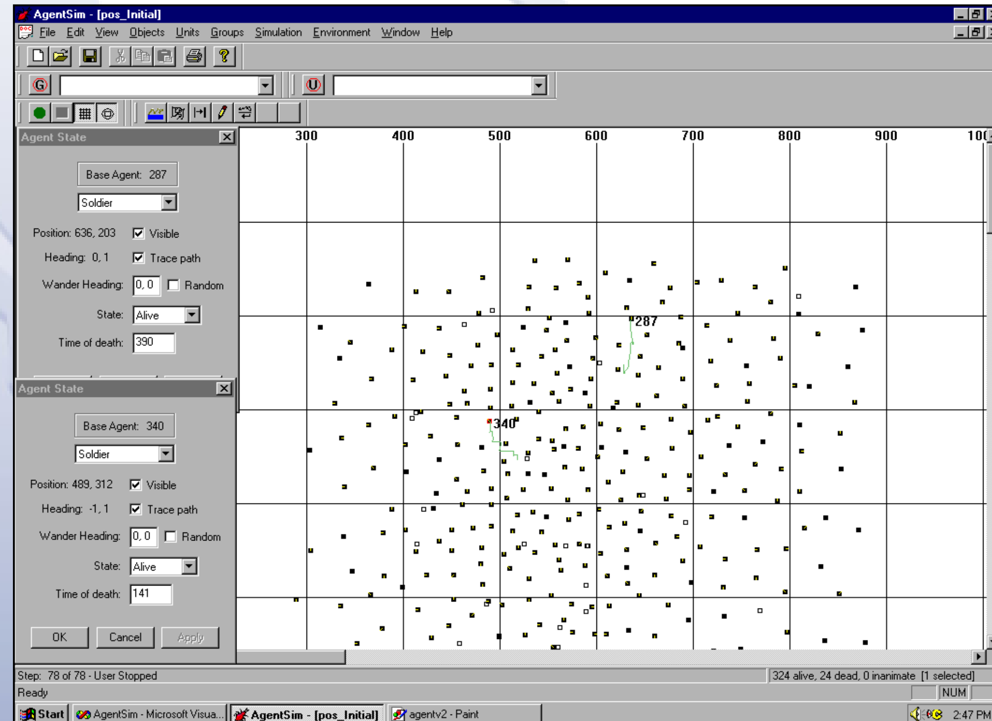
Robot Team

- Emergent Behavior
- High Fault Tolerance
- Redundancy
- Low Cost
- Modulated Diversity
- Cooperative Behavior



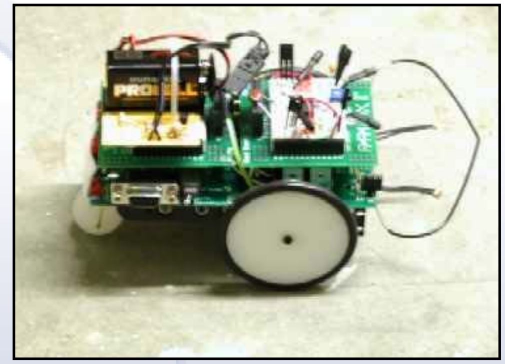
Social Potential Fields - Simulation Results

- **The Social Potential Fields method proved robust for maintaining spatial relationships between robots**
- **The Social Potential Field method is highly dependent on accurate neighbor detection. *Specifically, motion efficiency, relies greatly on sensor performance and coverage area.* A resulting behavior that emerges is "*Chattering*" in which a robot will continually chatter back and forth making little headway as neighboring agents are found, lost, and regained.**



AgentSim **- Simulation Framework**

Implementation



Communication
- IR
- Acoustic
- RF

Autonomous Behaviors

- IR obstacle avoidance
- Light Sensitivity

Collective Behaviors

1) Social Potential Fields

Repelling Arm:
- light sensors
- bump sensors
- IR sensors
- Audible "chirping"

Attractive Arm:
- Audible "chirping"

2) IR Following

Characterization

Spill Sensor:
- electronic contact to detect contact with water

Components of Swarm Intelligence

• Randomness	Light Responses
• Decentralization	Autonomous Behaviors
• Indirect Interaction	Chirping / Social Potential Fields
• Self-organization	Online Adaptation

Swarm Intelligence Experiment

- How does performance scale with the number of robots?
- How does reliability scale with the number of robots?
- Can we quantify "emergent" behavior?
- At what point do we see the maximum performance per robot?
- How long?

Team Performance --Initial Findings

1. <u>Interference</u>:
   - *Physical Interference*: The robots sometimes collided or became physically entangled with one another
   - *Chattering*: A phenomenon whereby robots hem each other in and, given sufficient obstacle and population density, essentially spin in place. Chattering wastes time and energy and hinders exploration of new ground. This is a phenomenon characteristic of social potential forces in systems. 2 It can be mitigated through omni-directional sensing, moment-type forcing function, or online learning.

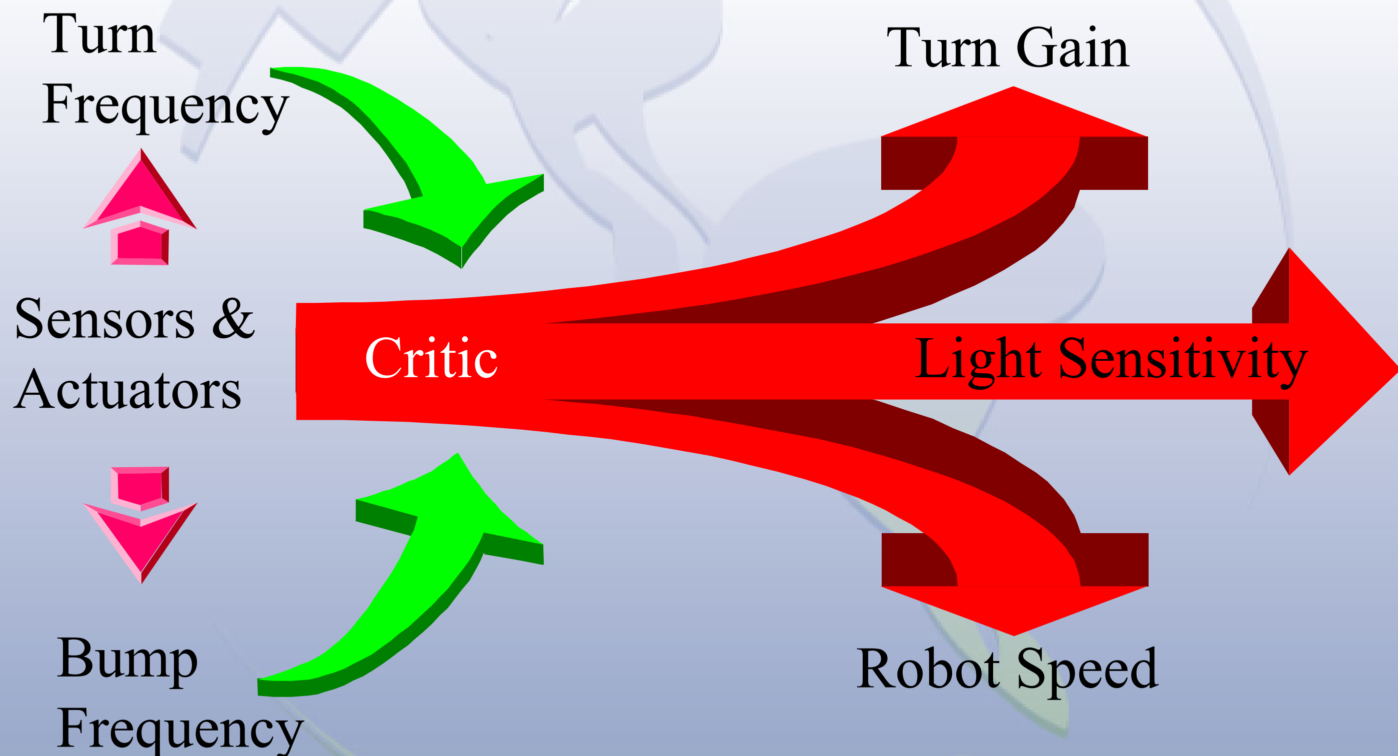
2. <u>Redundancy</u>: Robots tended to cover the same ground as their peers and fall into "ruts."

3. <u>Area Omission</u>: Each behavior tended to have its own Achilles' heel - a set of environmental conditions which it tended to avoid such as corners, shadowed/bright areas, or areas behind obstacles.

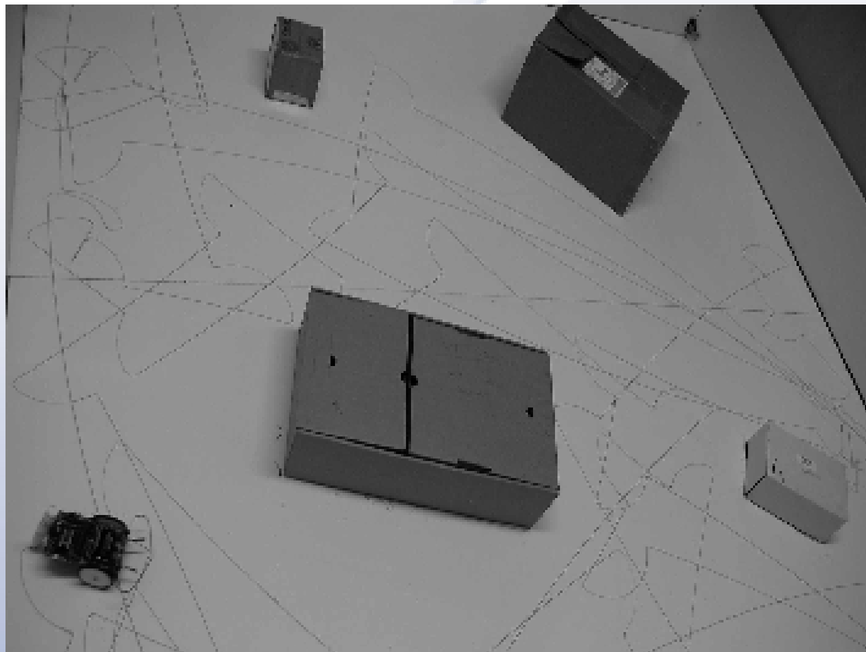
Beneficial Cooperative Behavior Requires...

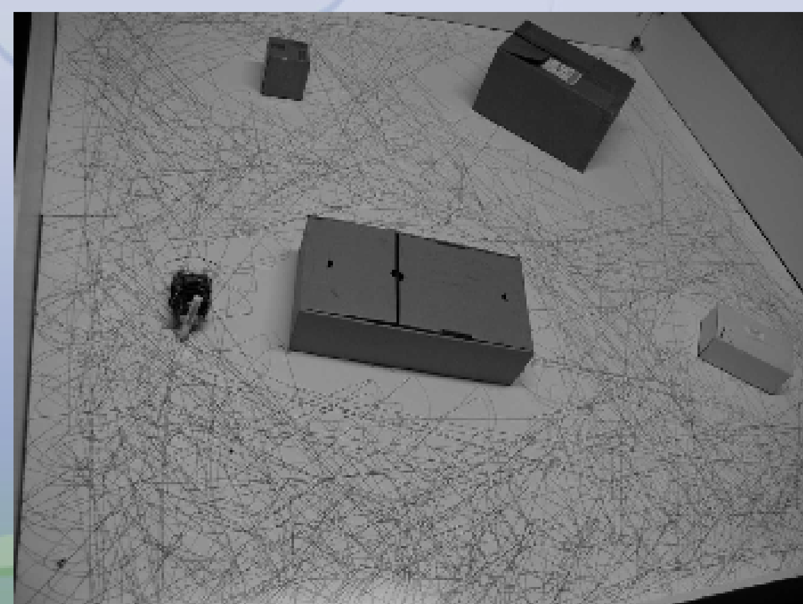
- Reduce redundancy and interference
- Maintain a beneficial level of social interaction
- Adjust each robot's willingness to explore the solution space
- Adapt individual robot behavior to varying environments and numbers of robots

Online Adaptation



Test-Bed Environment



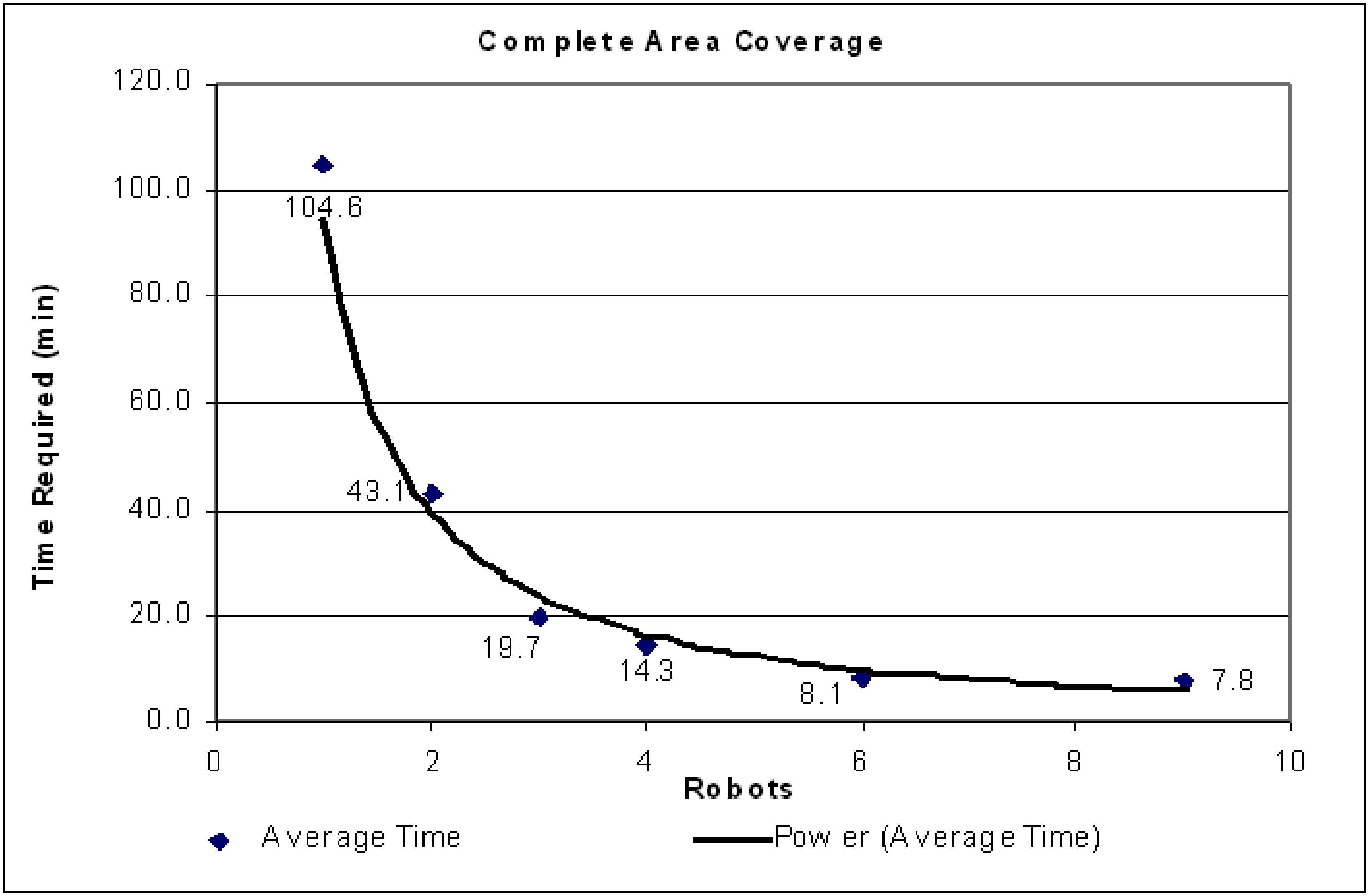


Experiment Results

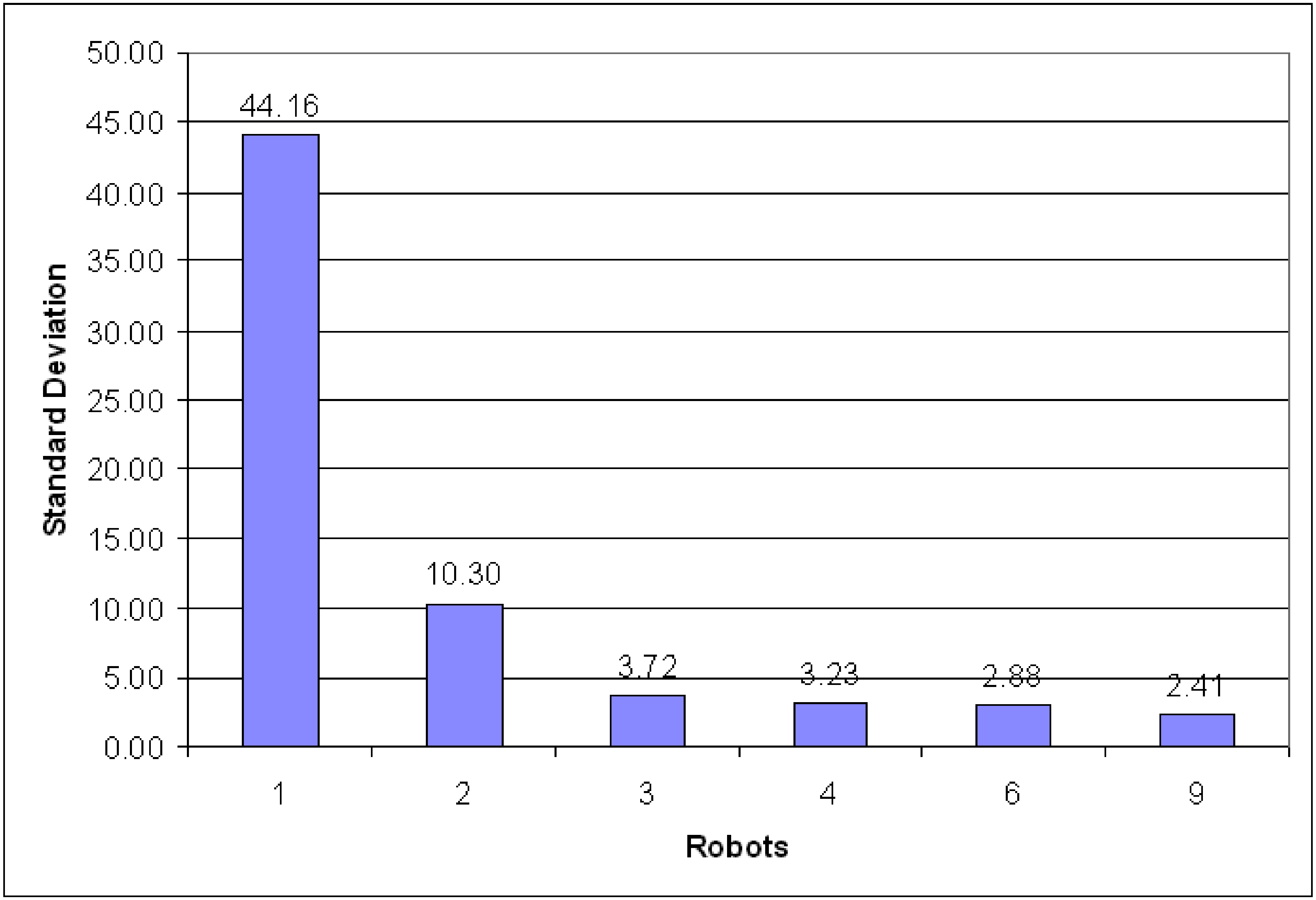
TIME REQUIRED FOR TASK COMPLETION (MIN)

Robots	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
1	77	53	110	113	170
2	33.78	56	50.93	42.33	32.67
3	21.93	24.63	18.47	14.93	18.33
4	14.9	12.63	10.25	14.76	19.0
6	6.53	6.46	6.78	7.58	13.20
9	11.75	6.36	8.02	5.47	7.63

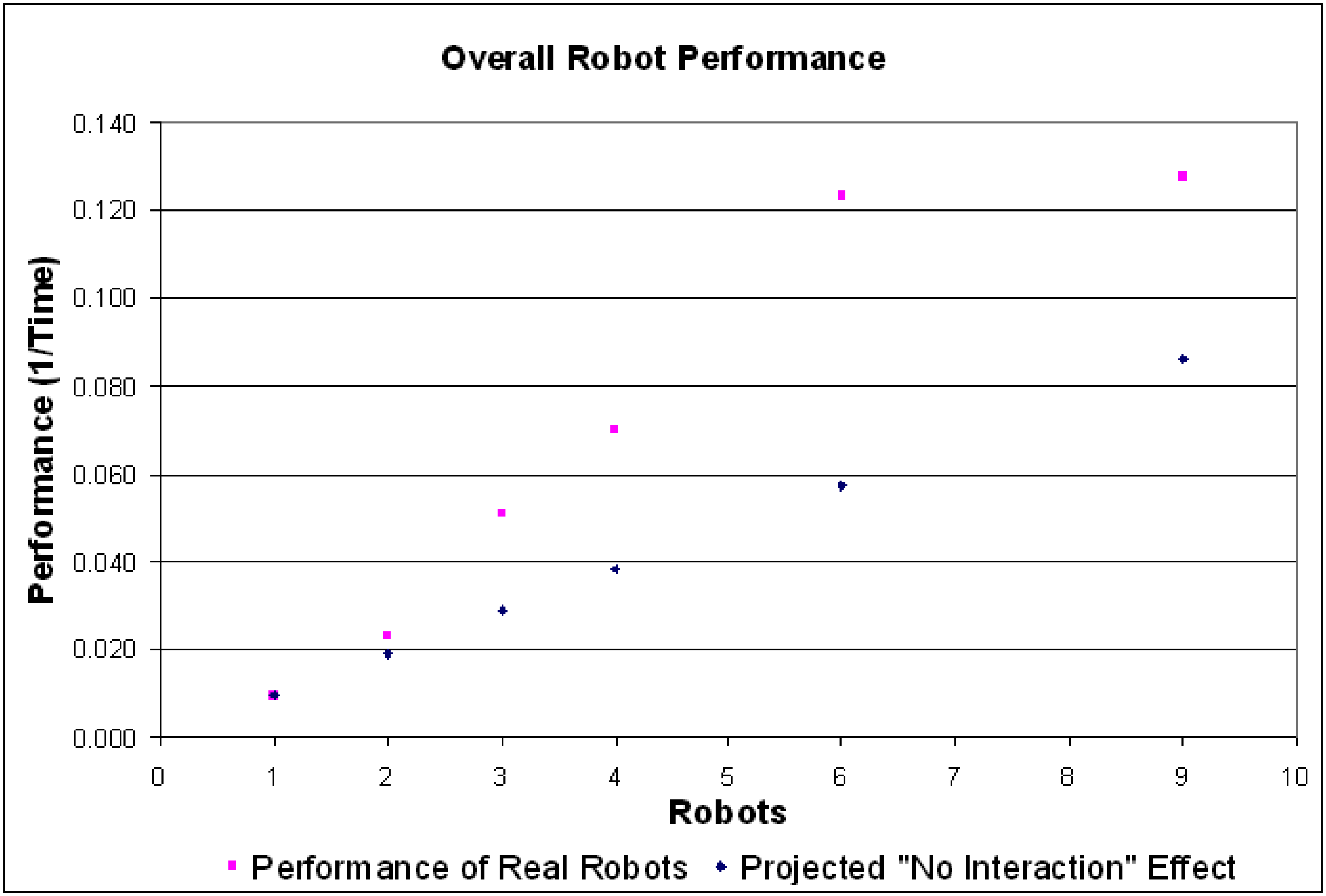
Graph of Time vs. Robots



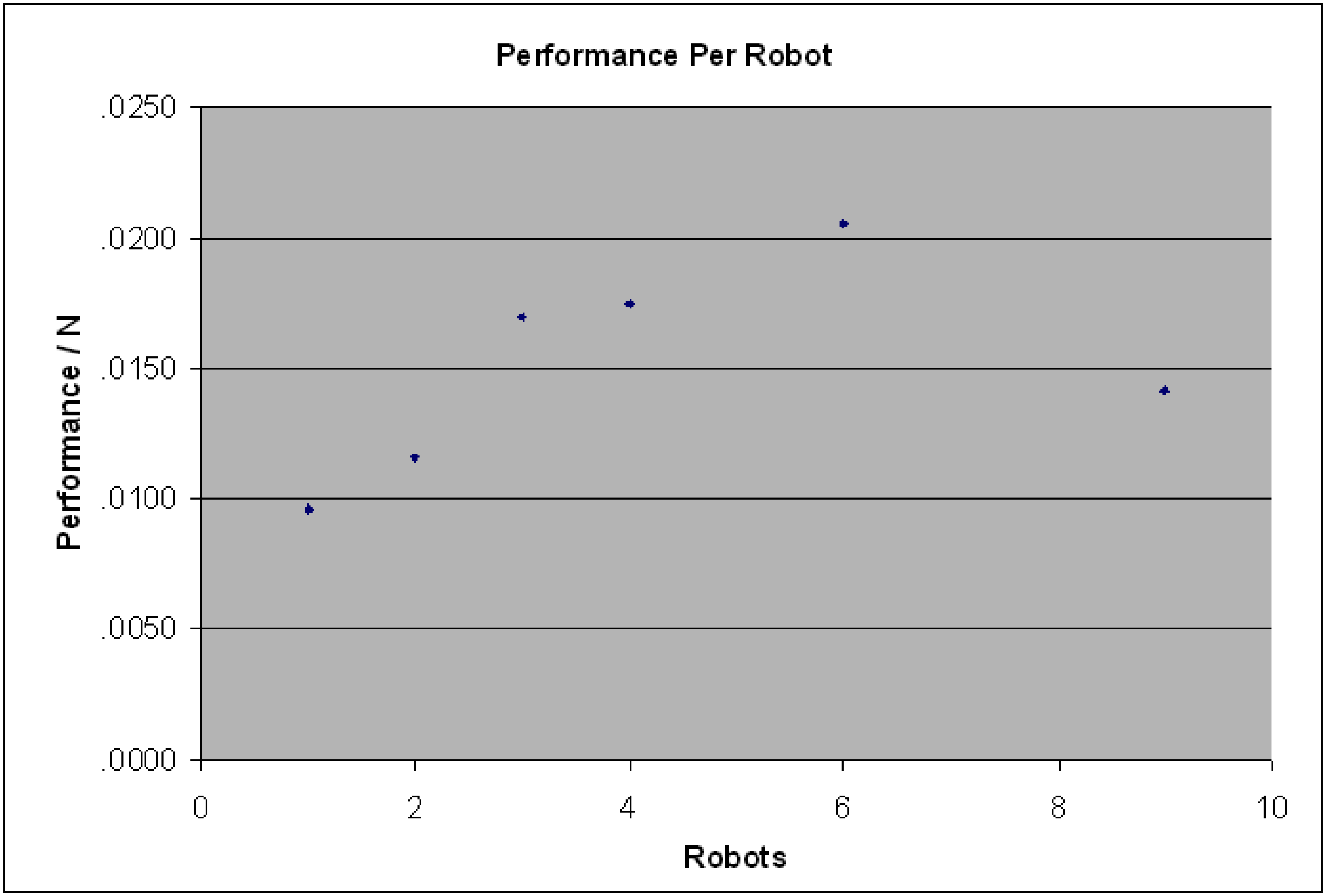
Standard Deviation (time)



Performance



Performance / n

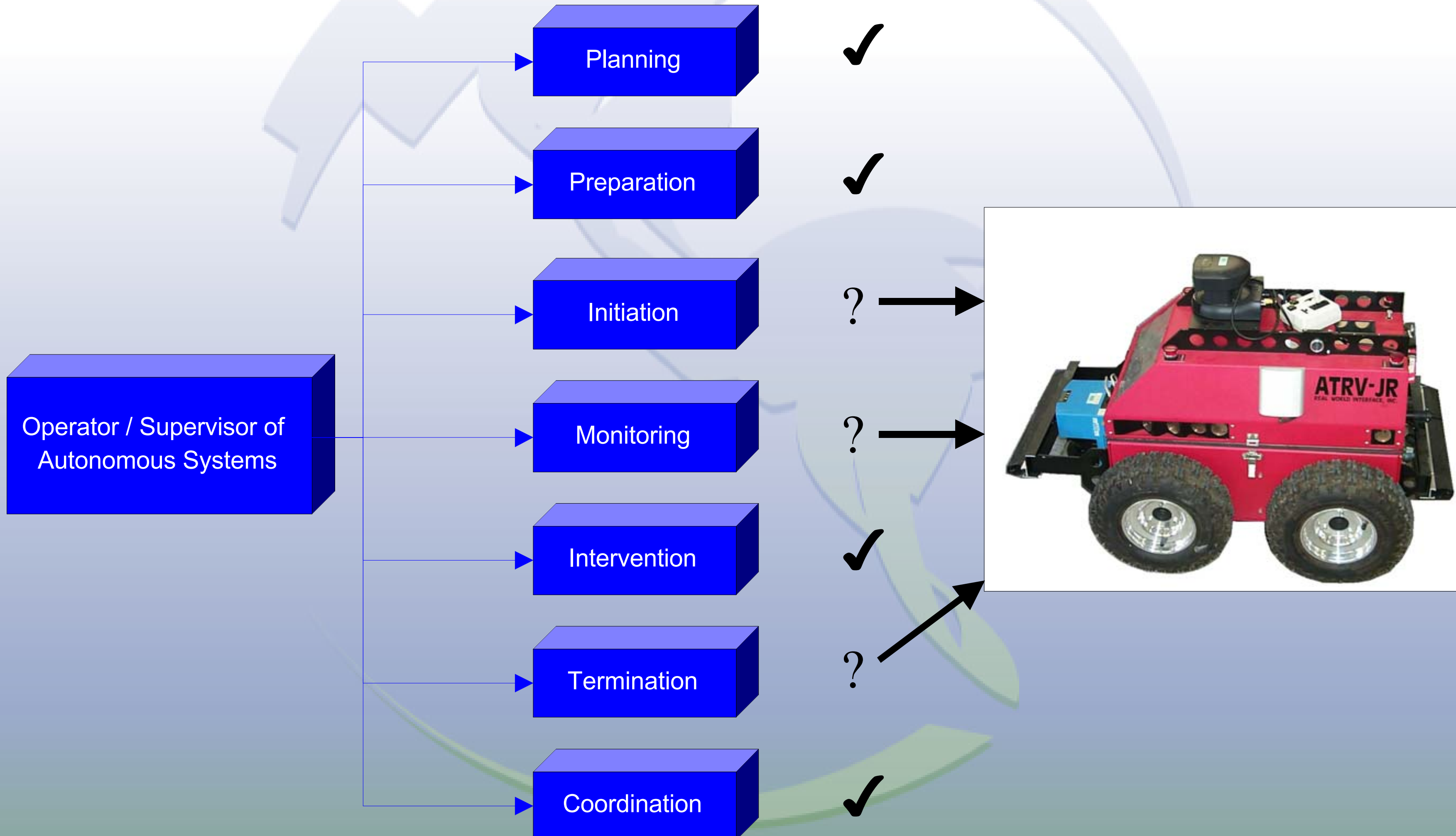


Out of the Testbed

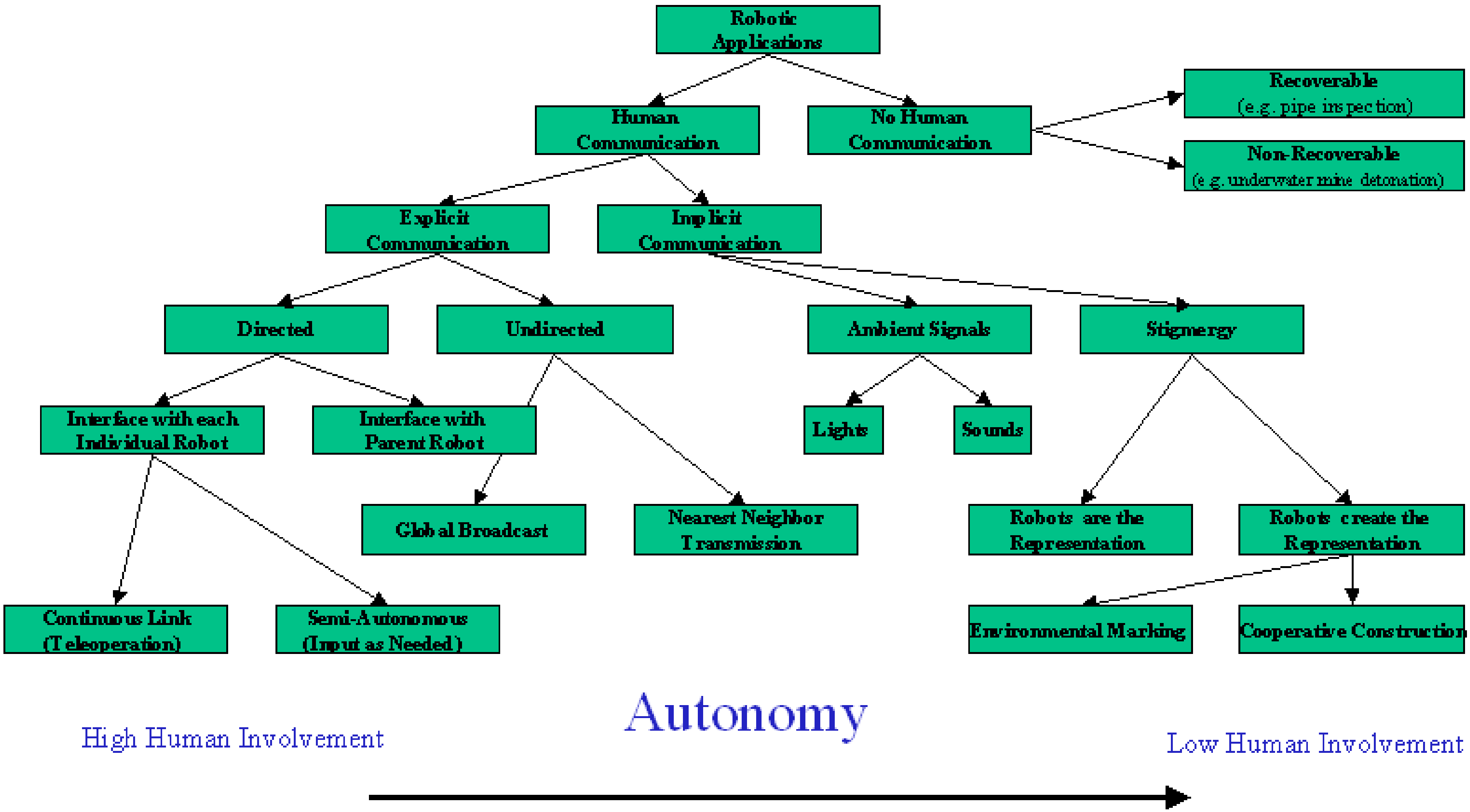
While this behavior set with online learning proved effective in the Testbed, it also transported well to other environments such as a typical warehouse floor.

But, what about deployment??

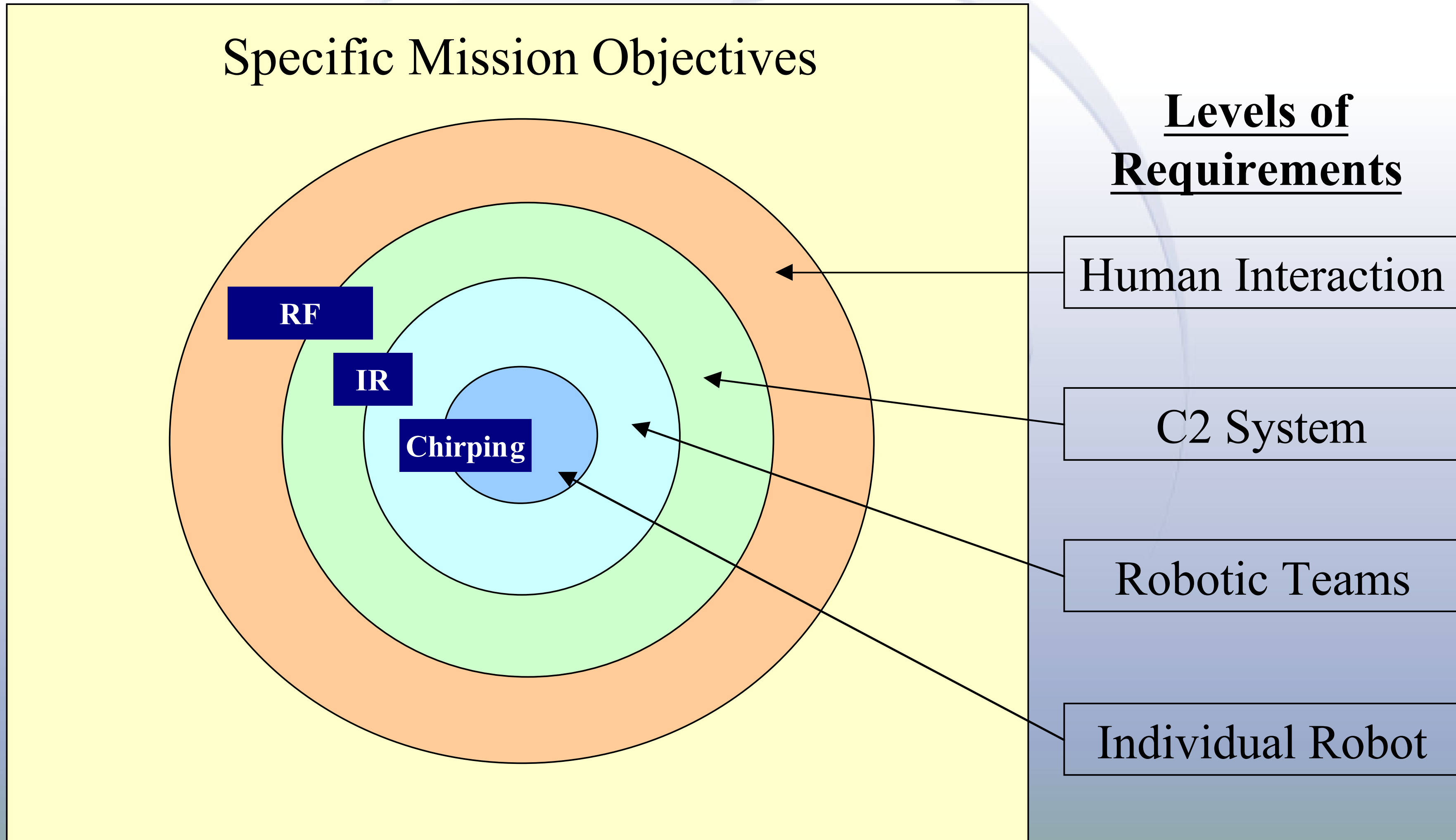
Operational Scenario



Communication Possibilities



Multi-Modal Comms for Mixed-Initiative Autonomy

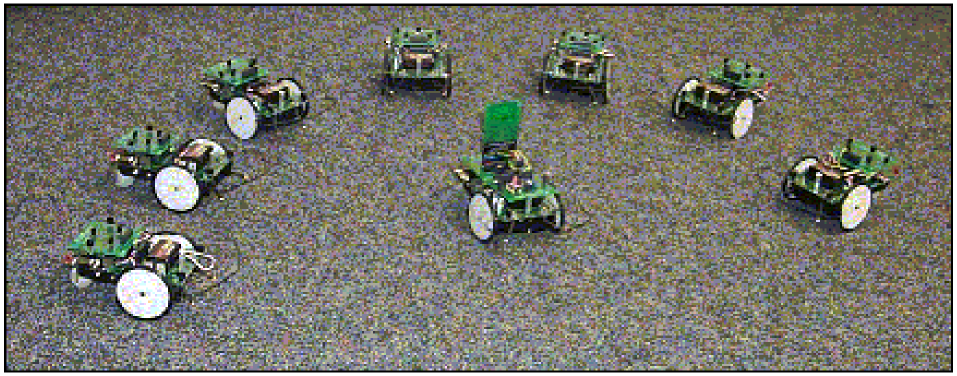


Mission tasking of robotic forces

Results & Conclusions

- A holistic approach is needed for developing distributed robotic systems and specifically to address the problem of human-robot interaction.
- Simulated and real world experiments indicate benefits of multi-robot strategies. Effective coverage can be achieved from a swarm of small, inexpensive robots.
- A Hierarchical Method of Command and Control is an effective means to group and task large scale robotic forces
- The Social Potential Fields method is robust for maintaining spatial relationships between agents
- Online learning can greatly enhance individual and collective performance including the mitigation of adverse effects such as chattering.

Future Work



1. Expand the size of our team of robots. Cross platform integration with other DR/SDR teams.
2. Human-Centric evaluation of AgentTools.
3. Further development of operator support tools.
3. Platform and Sensor exploration to move this project towards deployment in DOE hazardous environments.

Technology Transition Plan

The technologies and insight developed with this project are being used in conjunction with internal research conducted by the INEEL for developing cornerstone capabilities in cooperative robotics and application venues in support of the Department of Energy's (DOE) Robotics and Intelligent Machine (RIM) initiative. The control concepts and human interaction requirements are applicable for a diverse force of larger autonomous robots, which are also of interest to other government agencies.

Publications on Project Research

Dudenhoeffer, D. D. and M. P. Jones, 2000. **A Formation Behavior for Large-Scale Micro-Robot Force Deployment**. In Proceedings of the 2000 Winter Simulation Conference, eds. J. A. Joines, R. R. Barton, K. Kang, and P. A. Fishwick, 972-983, Orlando, Florida: Institute of Electrical and Electronics Engineers.

Hallbert, B. P., D. D. Dudenhoeffer, D. J. Bruemmer, M. L. Davis, and G. J. Khoury. 2001. **Human Interface Concepts for Autonomous/Distributed Robot Control**, INEEL/EXT-2001-00232, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

Dudenhoeffer, D. D., D. J. Bruemmer, M. O. Anderson, and M. D. McKayD. 2001, **Development and Implementation of Large-Scale Micro-Robotic Forces Using Formation Behaviors**, In Proceedings of SPIE, Unmanned Ground Vehicle Technology II, 4024. Bellington, Washington: SPIE- The International Society for Optical Engineering.

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Dudenhoeffer, D. D. and D. J. Bruemmer, and M. L. Davis. **Modeling And Simulation For Exploring Human-Robot Team Interaction Requirements**. Accepted for the 2001 Winter Simulation Conference, Washington DC, Dec 2001.

Bruemmer, D. J., D. D. Dudenhoeffer, M. O. Anderson, and M. D. McKay. **Components of Swarm Intelligence and their Effects on Performance of a Multi-Robot Team**. Submitted to IEEE Transactions on Robotics and Automation

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